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Asymmetric V-shaped streaks recorded on board DEMETER satellite above powerful thunderstorms

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[1] We report here observations of both symmetric and asymmetric forms of V-shaped streaks on VLF spectrograms recorded on board the DEMETER satellite. Recent investigations have shown that V-shaped streaks are associated with intense and numerous 0+ whistlers generated in the VLF range by active thunderstorms. To understand the origin of the different spectral forms of the V-shaped events, a systematic survey of these phenomena is performed by means of a visual inspection of the VLF spectrograms covering more than 5 years of DEMETER observations. Asymmetric events are more frequently observed over high-latitude regions. The influence of the magnetic field inclination on the observed asymmetry is investigated. First, a full wave method is used to compute, at the lower ionospheric boundary, the electromagnetic pattern that is due to a streak of lightning. This allows us to show a small asymmetry especially for high frequencies ($f > 10$ kHz). Then, cold plasma dispersive properties are used to determine the characteristics of the waves propagating from the mesosphere to the satellite altitude. We find that, at the plasma cutoff altitude, the propagation is more efficient for waves having wave-normal directions parallel, or quasi parallel, to the Earth's magnetic field direction. Finally, a detailed analysis of an asymmetric V-shaped event is performed. The precise localization of the lightning associated with the V-shaped event is provided by the METEORAGE network. A relationship between the local inclination of the magnetic field above active thunderstorms and the asymmetry of the V-shaped event is pointed out for this particular event.

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1. Introduction

[2] The Centre National d'Etudes Spatiales (CNES) DEMETER satellite is mainly devoted to studying ionospheric perturbations related to seismic and manmade activity; it also has the objective of studying the Earth's electromagnetic environment. Its payload consists of wave and particle analyzers described by *Cussac et al.* [2006, and references therein]. The major part of electromagnetic (EM) waves recorded by DEMETER in the ELF-VLF range consists of whistlers observed at low latitudes and midlatitudes during nighttimes [*Parrot et al.*, 2008a]. The propagation and effects of these waves have been studied by many authors since the pioneering work of *Storey* [1953] and the classical book by *Helliwell* [1965]. While lightning-generated wave energy propagating in the Earth-ionosphere waveguide is generally referred to as radio atmospherics (or sferics), on transionospheric penetration in the overlying magnetosphere the signal is said to become a 0+ whistler [*Smith and Angerami*, 1968]. In this context, the notation of 0+ signifies that the signal has directly reached the satellite over a short upward path.

[3] Adding to this long history, whistlers still attract active research. A first simultaneous observation on board the DEMETER satellite of newly injected 0+ whistlers and lightning- induced electron precipitation (LEP) is presented by *Inan et al.* [2007]. The causative lightning discharges are geolocated using the METEORAGE network [*Cummins et al.*, 1998; *Diendorfer*, 2002]. It has been shown that the region of precipitation is produced and maintained by a high rate of lightning within localized thunderstorm.

[4] *Parrot et al.* [2008b] have reported unusual V-shaped streaks observed on DEMETER VLF spectra above powerful thunderstorms during nighttimes. Similar V shapes in the frequency time spectrograms have been reported in the auroral zones by *James* [1976], but DEMETER observa-

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tions differ from the latter with their multiple V feature. The mechanism of generation is also different: While the V saucers have been associated with Čerenkov radiation produced by precipitating energetic electrons [*Ergun et al.*, 2001], the V-shaped streaks have been related to the high lightning rates of the thunderstorms acting as a nearly continuous broadband transmitter [*Parrot et al.*, 2008b]. The spectral features of the V-shaped streaks look like embedded V structures centered on a core of broadband intense 0+ whistlers. The V-shaped forms are composed of multiple independent bursts. The individual spectrum of each burst is regularly structured, with a quasi-periodic pattern of maxima. The location of these maxima depends on the distance from the source. *Parrot et al.* [2008b] interpreted them in terms of a mapping to high altitude of the frequency-dependent position of mode interference nulls (and crests) within the Earth-ionosphere waveguide. A recent model [*Lehtinen and Inan*, 2008] has been used to reproduce these V-shaped streaks; this model is based on a full wave method (FWM) in which the lightning activity is modeled as a vertical dipole emitting at continuous frequencies. From the work of *Parrot et al.* [2008b], we can conclude that the V-shaped observations are exclusively observed during nighttime (~2200 LT), corresponding to northward passes of the DEMETER satellite.

[5] This paper focuses on these V-shaped events associated with intense 0+ emissions and related to very active thunderstorms. The high lightning rate of powerful thunderstorms can act as a nearly continuous broadband transmitter emitting quasi-continuous electromagnetic impulses over more than 10 min in the Earth-ionosphere waveguide. Altogether, once they are displayed on a spectrogram, they form the V features. A detailed examination of the spectral forms of the V-shaped events observed on board DEMETER shows that they are distributed among three distinct classes: V-shaped symmetric events, V-shaped right asymmetric events, and V-shaped left asymmetric events. The purpose of the present paper is to investigate these phenomena and to test an explanation for the observed asymmetry.

[6] For the present study a database composed of all the V-shaped events recorded on board DEMETER during the period 2005–2010 has been built. The events were selected through a close inspection of the VLF spectrograms calculated from electric field data. The paper is organized as follow: In section 2 a short description of the DEMETER mission and of the electric field instrument (Instrument Champ Electrique (ICE)), is given and a typical example for each of the three classes of V-shaped events is presented. In section 3, the V-shaped event database is described and the statistical distribution of the three classes and their geographical localization are presented and discussed. The effect of the local magnetic field inclination on the asymmetry of the V-shaped events is investigated in sections 4 and 5. In section 4, the *Lehtinen and Inan* [2008] full wave propagation model is used to study the effect of the magnetic field inclination on the ELF-VLF electric field emitted by a lightning streak at the altitude of the lower ionospheric boundary. In section 5, the conditions of propagation from the Earth-ionosphere waveguide up to the satellite altitude are examined for a given location and density profile. In the first step, the crossing of the $X = f_{pe}^2/f^2 = 1$ plasma cutoff is investigated. Then the propagation from that boundary up to the DEMETER altitude, i.e., above the maximum of the *F* region, is studied. In section 6, a detailed analysis of an asymmetric V-shaped event is performed taking into account the lightning location provided by the METEORAGE lightning detection network [*Diendorfer*, 2002]. Finally, a summary and a discussion of the main results are given in section 7.

2. V-Shaped Emissions Observed by DEMETER

2.1. The DEMETER Experiments

[7] DEMETER is a low-altitude satellite launched in June 2004 into a polar Sun-synchronous orbit at an altitude of ~700 km. The main objective of the DEMETER satellite is the systematic investigation of the electromagnetic wave emissions observed during seismic activity and volcanic eruptions [*Němec et al.*, 2008]. Ionosphere and upper atmosphere disturbances are investigated, as well as the precipitation of associated particles. DEMETER is also dedicated to the survey of the electromagnetic environment of the Earth and to further investigating the impact of human activity on the ionosphere [*Parrot et al.*, 2007]. The DEMETER satellite carries scientific instruments measuring the fluctuation of the three components of both electric and magnetic fields. The magnetic field experiment, the Instrument Magnetic Search Coil (IMSC)< is described in detail by *Parrot* [2006], and the electric field experiment ICE is described by *Berthelier et al.* [2006]. All the data are collected at invariant latitudes up to 65°. DEMETER has two scientific modes of operation: A burst mode, which provides high-resolution waveform data, is triggered when the satellite is above seismic zones and other given specific zones; and a survey mode, which provides averaged power spectra. The frequency ranges covered are from DC to 3.5 MHz for the electric field measurements (ICE) [*Berthelier et al.*, 2006], and from a few hertz to 20 kHz for the magnetic field measurements (IMSC) [*Parrot et al.*, 2006].

[8] The DEMETER data, which are mainly used in the present paper, are the electric wavefield measurements performed from the ICE experiment. The ICE experiment consists of four sensors formed by spherical aluminum electrodes with embedded preamplifiers, mounted on the ends of 4 m long booms, with their associated electronics. It covers the frequency ranges DC–3.5 MHz. However, studies of V-shaped events are performed in the VLF frequency range only, i.e., in the frequency band running from a few hertz to 20 kHz. Considering the time duration of a V-shaped event (several minutes), the spectrograms are computed from survey mode data. The considered wavefield component is the field component perpendicular to the orbital plane. The frequency resolution of the spectrograms is 19.53 Hz, and the time resolution is 2.048 s. In order to check the electromagnetic nature of the V-shaped events, VLF magnetic wavefield data are also used. They are provided by the IMSC experiment [*Parrot et al.*, 2006] with the same frequency and time resolutions as those for the electric data.

2.2. V-Shaped Events Recorded on Board DEMETER

[9] In this section a description of the spectral forms of the V-shaped emissions observed on board DEMETER is given. VLF spectrograms of the electric field recorded

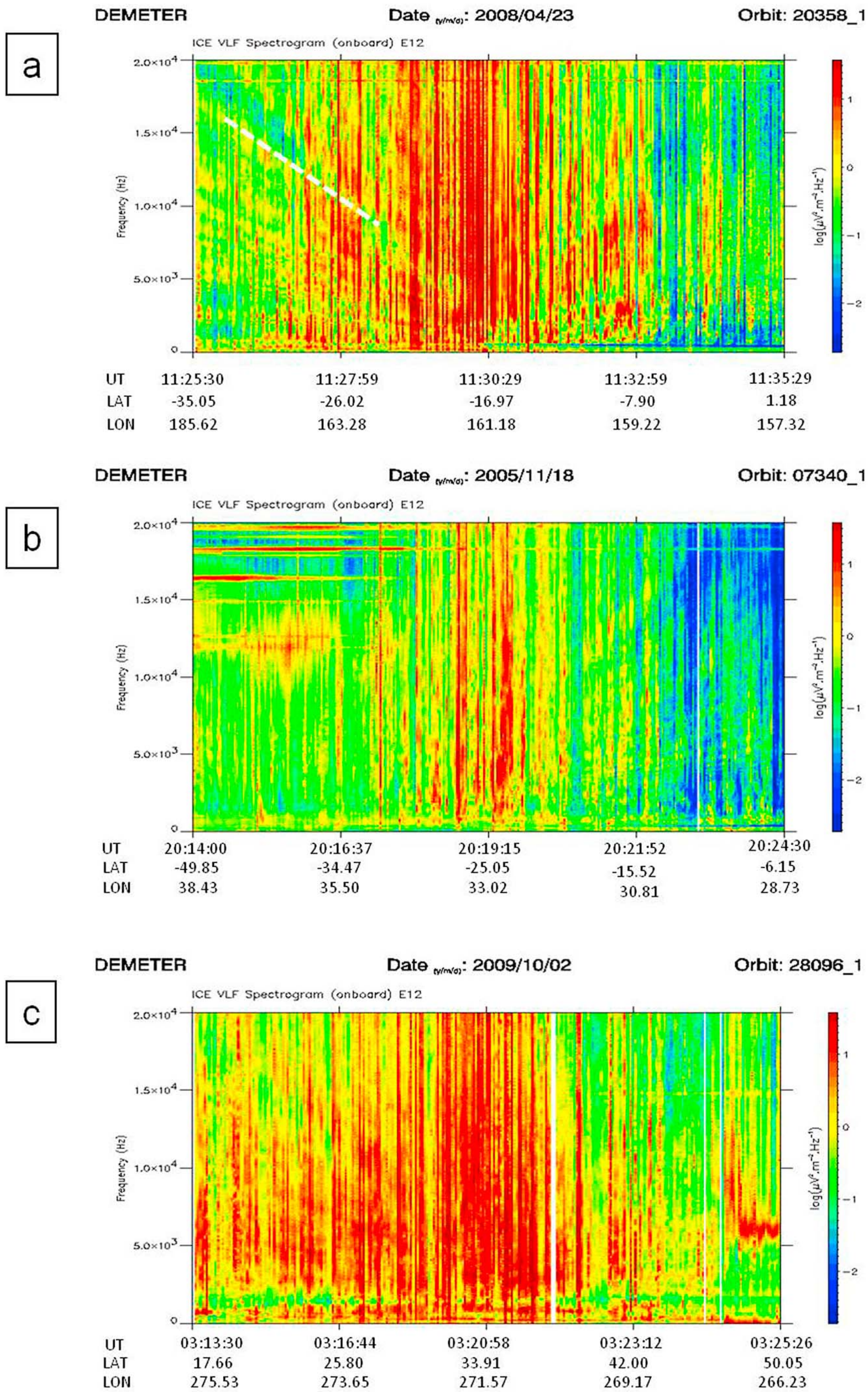

Figure 1. Spectrogram of an electric field component in the VLF range up to 20 kHz for three typical events. The intensity of the electric field is given by the color scale at right and is expressed in $\mu V^2\ m^{-2}\ Hz^{-1}$. The parameters below the spectrograms indicate universal time (UT), local time (LT), and geographic latitude and longitude. (a) A symmetric example observed on 23 April 2008. (b) A right asymmetric event observed on 18 November 2005. (c) A left asymmetric event for 2 October 2009. The white dashed line in Figure 1a underlines an arm on the V pattern of the symmetric observation.

during three representative V-shaped events are displayed in Figure 1. All the observations are made around ~2200 LT and correspond to a south to north path of the DEMETER satellite. The frequency range is 1–20 kHz, and the intensity of the electric field is color coded according to the scale to the right of the panels. Universal time and geographic latitudes and longitudes are indicated at the bottom of the figure. We can notice that the V-shaped emissions are typically observed on board DEMETER over ~10 min time interval that corresponds to a geographical distance of thousands of kilometers. As shown by *Parrot et al.* [2008b], the V-shaped signature is formed by several arms. Each arm shows the frequency-dependent position of interference modes within the Earth-ionosphere waveguide. The same V-shaped structures are seen on the spectrograms derived from the measurements of the magnetic wavefield (IMSC). However, because of the presence of satellite-generated interference lines and the sensitivity of the magnetic antennas, they appear less clearly. These observations on the IMSC spectrograms point out that the V-shaped streaks events are electromagnetic events.

[10] A symmetric V-shaped event is represented in Figure 1a. It corresponds to electric field measurement performed on 23 April 2008, between 11:25:30 UT and 11:35:29 UT. Several 0+ whistlers occur during this interval. Their number and their intensities reach a maximum value around 11:30:29 UT when the satellite is above the Australian continent. Different arms are observed before and after the intensification of the signal, leading to a symmetric form in the spectrogram. One of the arms of the V pattern is underlined in the spectrogram with a white dashed line.

[11] An asymmetric V-shaped event is shown in Figure 1b. It was recorded in the Southern Hemisphere on 18 November 2005, from 20:14:00 UT to 20:24:30 UT. Many 0+ whistlers occur during this time interval, with higher occurrences on the right-hand side of the spectrogram. The intensification of the signal takes place at 20:19:15 UT. Only the right-hand side of the usual V pattern is observed between 20:19:15 UT and 20:24:30 UT. No arms are observed on the left-hand side of the spectrogram between 20:14 UT and 20:19 UT. The resulting spectrogram depicts a right asymmetric V-shaped emission.

[12] A second type of asymmetric V-shaped event is presented in Figure 1c. It was recorded in the Northern Hemisphere on 20 October 2009 from 03:13:30 UT to 03:25:26 UT. Intensification of the 0+ whistlers occurs around 03:20:58 UT. Only the left-hand side of the usual V-pattern is observed between 03:13:30 UT and 03:20:58 UT. No arms are observed on the right-hand side of the spectrogram. The resulting spectrogram depicts a left asymmetric V-shaped emission.

[13] The three events presented in this section are typical examples of the V-shaped observations on board the DEMETER satellite. They are observed on nighttime orbits around 2200 LT. Asymmetric V-shaped events are reported here for the first time. The denominations left asymmetric and right asymmetric are based on the spectral form observed on the DEMETER spectrograms.

[14] In section 3, a statistical study giving the geographic localization of the different spectral signatures is presented and discussed.

3. Statistical Features of the V-Shaped Events

[15] In order to understand the characteristics of the three classes of V-shaped events, a systematic study of nighttime observations was performed over five and a half years of data. A database of the events was constructed by means of an online visualization of the spectrograms corresponding to nighttime observation. *Parrot et al.* [2008b] analyzed DEMETER data for the period January 2005 to October 2007, detecting 87 events. In the frame of this paper we have extended the database by including the time period November 2007 to November 2010, detecting 296 events. The studied database in this paper is composed of these 383 distinct events.

[16] To localize geographically all the V-shaped observations, the position of the satellite was determined at the reference time T_{ref}. For a symmetric V-shaped event, T_{ref} is defined as the time for which the left and right arms are joining. Simultaneously, we observe around this time a clear intensification of the 0+ whistlers (both in power and occurrence rate). The T_{ref} definition is extended to the left and right asymmetric observations by considering it as the time for which the arms are reaching their lower frequency in the spectrogram representation. The corresponding orbital parameters were determined from the orbital files provided by the DEMETER data center [*Lagoutte el al.*, 2006].

[17] All the observed events are displayed in the geographical map of Figure 2. The three classes of events (symmetric, left asymmetric, and right asymmetric) are represented by blue, green, and red squares, respectively. One first notices that, with 71% of the total of V-shaped events observed, a major part of the observations occurs in the Northern Hemisphere. The ratio of the observations over land and those over oceans is about 17/1, with 362 events observed over lands (Northern and Southern Hemispheres) and 21 over oceans. This is in agreement with the observation that lighting activity is more important above the continents than above the oceans (for *Christian et al.* [2003], the land/ocean ratio is about 10/1).

[18] By comparing the localization of the V-shaped events displayed in Figure 2 with the lightning occurrence rates determined by optical lighting flash detectors [see *Christian et al.*, 2003, Figure 4], we can make the following statements:

[19] 1. The V events, represented by green, red, and blue squares (see, for example, U.S. central regions, China, South Africa, west of Brazil) are correlated with regions with high occurrence rates of thunderstorm lightning.

[20] 2. As expected, the V-shaped events are mainly observed above continents where most of the active thunderstorms occurred. The high amount of V events detected by the DEMETER satellite above the United States and the eastern coasts of the continents is fully consistent with the lightning flash distribution, as evidenced by *Christian et al.* [2003].

[21] However, only 13 V-shaped events were detected above the tropical region (within ±10° of geomagnetic latitude) where the most active thunderstorm areas are located. This lack of observation is explained by the fact that at low latitudes the inclination of the geomagnetic field is very small and the penetration condition of VLF waves through the ionosphere is very difficult to achieve. The only remaining areas in the Northern and Southern hemispheres where V-shaped observation occurred are in geographic latitude ranges [+20°, +60°] and [−60°, −20°], respectively. In these regions the thunderstorm activity is reasonably high (above continents) and the penetration condition of VLF waves into the ionosphere is allowed.

[22] The seasonal effects on the V-shaped emission have also been studied. The V-shaped events are mostly observed in the Northern Hemisphere for the period May–October, when the lightning activity is the highest. For the Southern

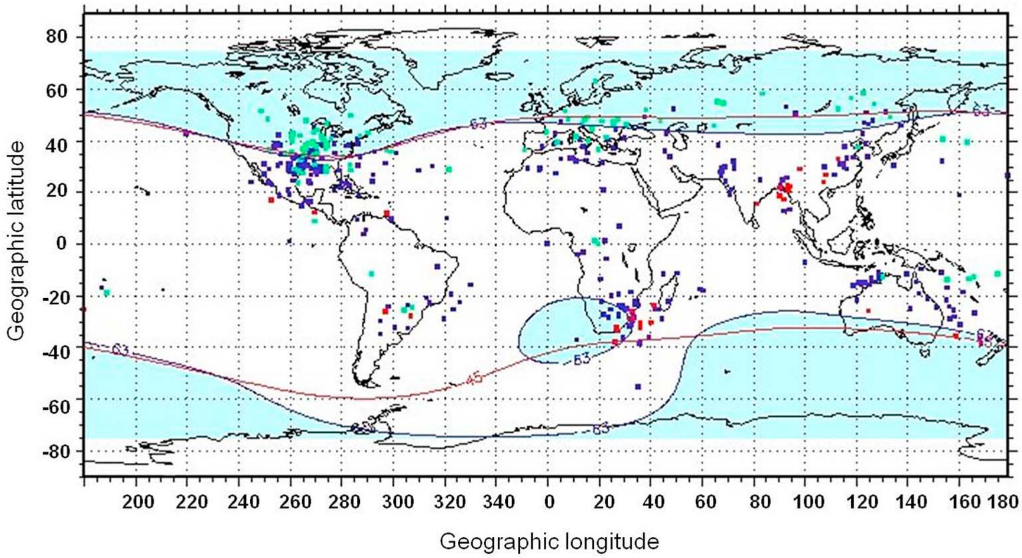

Figure 2. Geographical location of the 383 observations of V events during the period 2005–2010. Symmetric, right, and left asymmetric V-shaped events are indicated by blue, red, and green squares, respectively. The red lines indicate the corrected geomagnetic latitude denoted as lat_{CGM} (calculated using an IGRF model for the magnetic field) at 45° and −45°. Blue zones correspond to regions with high values of the inclination ($I > |63°|$).

Hemisphere, the V-shaped events are more often observed during the summer.

[23] By examining the geographical distribution of the three classes of events, one may notice that the asymmetric ones are more frequently observed at geographic latitudes approximately greater than 40°. This is made clearer when using *Baker and Wing*'s [1989] corrected geomagnetic coordinates, where lat_{CGM} is the corrected latitude. Considering the isocontours at −45° lat_{CGM} and 45° lat_{CGM} (red curve) in Figure 2, one notes that the occurrence of asymmetric events is more important for high geomagnetic latitude regions, $||lat_{CGM}| > 45°$. More specifically, in the Northern Hemisphere, 62% of the total of V-shaped emissions (72 events) are left asymmetric events (green squares).

[24] As a matter of fact, the magnetic field inclination was found to be a much more relevant parameter than the geographic and the corrected geomagnetic latitudes for characterizing the geographical areas of the three classes of V-shaped events. To do so, the magnetic field inclination around the globe was computed from the International Geomagnetic Reference Field-11 (IGRF-11) model [*Finlay et al.*, 2010]. By defining high-inclination regions as regions for which the magnetic field inclination is greater than 63° (a threshold value determined statistically), three high-inclination regions are delimited (in blue in the map of Figure 2): the northern region, the southern region, and a region in the southwest part of the South Atlantic Anomaly. The remaining region (in white) corresponds to the middle- and low- inclination regions. The occurrences of the different classes of events were calculated in three different areas. The first one corresponds to the high-inclination regions in the Northern Hemisphere ($I > 63°$), the second one corresponds to the high-inclination regions in the Southern Hemisphere ($I < -63°$), and the last one corresponds to the middle- and low-inclination regions ($-63° < I < 63°$); these results are reported in Table 1. About 56% of the 111 events observed in the high-inclination region of the Northern Hemisphere are left asymmetric V-shaped events. The remaining observed events are symmetric ones (44%). In the region with small and moderate values of magnetic field inclinations, 255 events were observed, most of them symmetric ones (77%); the remaining events are right asymmetric ones (10%) and left asymmetric ones (13%). Looking to the occurrences in the high- inclination values regions in Southern Hemisphere, only 22 V-shaped events are observed. Among them, 64% are symmetric V-shaped events. The remaining events (36%) are all right asymmetric events. No left asymmetric events are observed in the Southern Hemisphere.

[25] Some preliminary conclusions can be presented based on this statistical study: (1) V-shaped events are clearly correlated to the regions of high lightning activity. Accordingly they are observed mainly above continent. (2) Despite the high lightning levels in the equatorial region, very few V-shaped events are observed between −10° and 10° geomagnetic latitudes. For this region the geomagnetic field is

Table 1. Occurrence of the Three Classes of Events (Symmetric, Left Asymmetric, and Right Asymmetric) in the Three Regions Defined by the Values of Magnetic Field Inclinations *I*

Inclination[a]	Symmetric 256 EVT	Left Asymmetric 98 EVT	Right Asymmetric 29 EVT
High inclination ($I > |63°|$) NH 111 event	44%	56%	0%
Middle and low inclination $I < |63°|$ 250 event	77%	13%	10%
High inclination SH 22 evt ($I > |63°|$)	64%	0%	36%

[a]NH, Northern Hemisphere; SH Southern Hemisphere.

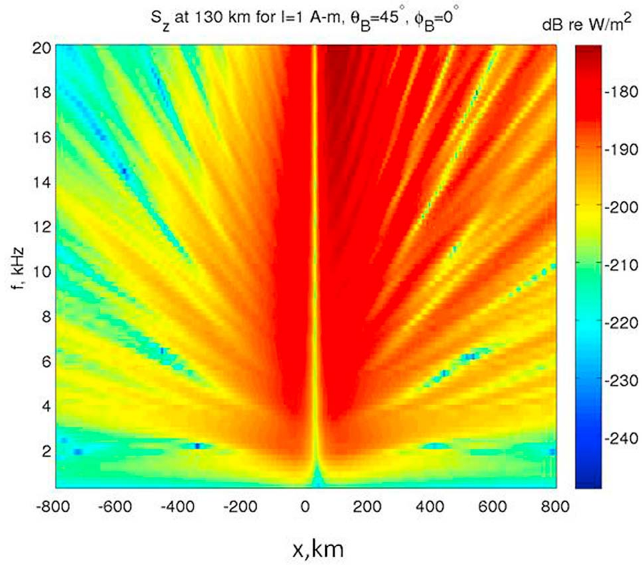

Figure 3. Modeling of the V-shaped form observed in Figure 1b using the FWM of *Lehtinen and Inan* [2008]. The figure represents the whistler mode wave intensity at 120 km altitude as a function of horizontal distance x from a ground-based point vertical dipole source. Calculation is done when the source is right below the satellite and for a magnetic field orientation of 45°.

almost horizontal, and the vertical propagation of VLF waves through the ionosphere is very difficult. (3) Asymmetric events are mainly observed in region with high values of geomagnetic latitude and are also associated with high values of the inclination of the magnetic field. Hereafter we investigate the possible relationship between the spectral signature of the observed V-shaped events and the local configuration of the magnetic field.

4. Propagating Fields Using Full Wave Model and Comparison With Observations

[26] In this section, the expected VLF wavefield generated by lightning sources is computed just above the lower ionosphere boundary. The computation is performed using *Lehtinen and Inan*'s [2008] full wave method (FWM). The FWM used is based on a full wave finite element approach to calculate the electromagnetic wavefield in a horizontally stratified ionosphere treated as magnetized plasma. The electromagnetic wavefields are calculated both in the Earth-ionosphere waveguide and in the ionosphere (as an upward propagating whistler mode). This model has previously been used to compute the ELF and VLF waves radiated from modulated HF-heated electrojet currents [*Lehtinen and Inan*, 2008]. Some numerical improvements to the FWM have been introduced by *Lehtinen and Inan* [2009]; the model correctly reproduces the transionospheric propagation of VLF electromagnetic waves from ground-based transmitters up to satellite altitudes. More recently, the FWM has also been used to compute the VLF field in the near zone of ionospheric disturbances created by lightning electromagnetic pulses [*Lehtinen et al.*, 2010]. Looking to the V-shaped streaks, *Parrot et al.* [2008b] show that the FWM correctly reproduces the V-shaped emissions.

[27] In this paper, a local magnetic field with a significant inclination is considered in the model. The obtained results are then compared with DEMETER asymmetric V-shaped observations.

[28] The model is applied to the radiation of ELF and VLF waves from a lightning source. The lightning source is modeled as vertical dipole source radiating equal power at all frequencies. The distribution of the electromagnetic field created by the lightning is then computed for any uniform horizontal plane. In the vertical z direction, the changes in the medium are described as different layers with fixed dielectric permittivity in each one. According to the Snell law, the horizontal component of the wave vector is conserved during propagation through all layers. After separating the electromagnetic field in downward and upward propagating modes, the wave amplitudes are calculated by a recursive method. The fields in adjacent layers are related by the conservation of the electric and magnetic field components parallel to the interface of the layers of the model. Electric and magnetic field amplitudes are finally computed at each point of the (x, y) grid by the inverse Fourier transform method.

[29] The present simulation was performed considering a local magnetic field with an inclination angle of 45° with respect to the zenith. Such a configuration corresponds to the magnetic field configuration encountered in the Southern Hemisphere. The results are shown in the spectrogram of Figure 3. The intensity of the signal, computed at each point of the grid, is displayed with respect to the horizontal distance to the source region in a color code for the frequency range 1–20 kHz. Because of the numerical limitations linked to the size of the grid, simulation had to be stopped at an altitude of 120 km, i.e., at the bottom of the ionosphere, just above the layer of collisional absorption. However, despite this limitation, results of the simulations at 120 km give useful information about the spectral forms observed. At this altitude, the whistler mode waves have already started their propagation in the ionosphere, after transmission from the Earth-ionosphere waveguide. The V-shaped pattern is reproduced in the spectrogram of Figure 3. The intensity of the whistler mode waves shows an asymmetry more pronounced at the highest frequencies (f > 10 kHz). For instance at f = 16 kHz, the intensity is higher for positive x values compared with negative x values. The simulated spectrogram is in agreement with the right asymmetric observations on board the DEMETER satellite. Nevertheless, we still have to explain the pronounced asymmetry observed on DEMETER spectrograms where the whole left-hand side of the V pattern is not observed. Some insight on about how the waves propagate to satellite altitude is presented hereafter, using the cold plasma theory for the computation of the modes propagating to the satellite altitude.

5. Cold Plasma Calculation of VLF Propagation From the Mesosphere up to the Satellite Altitude

[30] The only waves that penetrate the ionosphere and propagate farther up to the satellite altitude are those that cross the $X = f_{pe}^2/f^2 = 1$ plasma cutoff. The existence of that boundary has been pointed out by *Ellis* [1956]. In his radio-

window concept, *Budden* [1985] showed that when collisions are taken into account, wave energy is transferred through the $X = 1$ plasma cutoff for wave-normal vectors in a small cone of angles around B_0, $\theta = (k, B_0)$. Once the boundary has been crossed, the propagation characteristics are computed using a cold plasma model. In a recent paper, such a VLF upward propagation filtering system was shown to be fully consistent with the DEMETER observations [*Lefeuvre et al.*, 2009]. This model is based on a magnetized cold plasma description including collisional terms. The refractive index n is given by the Appleton-Lassen formula [*Budden*, 1985], which is a function of the plasma frequency f_{pe}, the electron gyrofrequency f_{ce}, the frequency of collisions υ, and the θ angle between the magnetic field B_0 and the wave normal k. The variation of the refractive index is thus given by

$$n^2 = 1 - \frac{A(X)}{B(X, Y, \theta) \pm C(X, Y, \theta)}, \tag{1}$$

with $X = f_p^2/f^2$ and $Y = f_{ce}/f$. $A(X)$, $B(X, Y, \theta)$ and $C(X, Y, \theta)$ are given by

$$A(X) = X(U - X), B(X, Y, \theta) = U(U - X) - \frac{Y_T^2}{2},$$

and

$$C(X, Y, \theta) = \left(\frac{Y_T^4}{4} + Y_L^2(U - X)^2\right)^{1/2},$$

where $Y_T = Y \sin\theta$, $Y_L = Y \cos\theta$, $U = 1 - iZ$, and $Z = \upsilon/2\pi f$.

[31] The collision frequency is given by the Wait and Spies formula, which is an adequate analytical form for the low ionosphere collision frequency during quiet periods [*Wait and Spies*, 1964; *Inan*, 1990]: $\upsilon = 5.10^6 \exp\{-0.15(h - 70)\}\mathrm{s}^{-1}$, where h is the altitude expressed in kilometers.

[32] To compute the propagating modes, accurate values of the plasma frequency and the electron gyrofrequencies are needed. We use values corresponding to a V-shaped observation on board the DEMETER satellite on 30 May 2008 around 21:00 UT and at 50° N 7°E. The plasma frequency is derived from the density profile given by the IRI 2007 model [*Bilitza and Reinisch*, 2008], and the magnetic field B_0 is given by the IGRF-11 model [*Finlay et al.* 2010]. Variations of the plasma frequency and the electron gyrofrequency with the altitude are represented in Figure 4a. The density profile (a red line) shows the characteristic E and F layers of the ionosphere, with a thickness of the E layer of the order of 50 km followed by a valley with the same thickness between the E and F layers. These variations are then used to compute the real and imaginary parts of the refractive index n.

[33] In the general case, two solutions labeled M+ and M− and corresponding to the plus and the minus signs in the denominator of (1) exist. For the VLF range, it can be shown that the VLF waves generated by lightning discharges on the atmosphere (corresponding to small values of density, i.e., $X \sim 0$) will have the possibility to propagate through the ionosphere (corresponding to higher values of density i.e., $X > 1$) only for the M+ mode. VLF waves corresponding to the M− mode are reflected at the bottom layer of the ionosphere. As shown by *Budden* [1985], when collisions are taken into account the upward propagating waves are filtered at the bottom of the ionosphere, depending on their θ values. This point is displayed in Figure 4b for the M+ mode, where the variations of the real and imaginary parts of the refractive index are given for $f = 10$ kHz and various values of θ (0°, 19°, 20°; 40 ° and 60°). A strong decrease for the imaginary part of the index corresponds to a high absorption. The absorption depends on the θ value: a low absorption between 0° and 20° and a higher (one order of magnitude) absorption for larger angles. This high value of absorption at 80 km (the bottom of the E layer) indicates that in this region the waves in an oblique propagation with respect to the magnetic field are absorbed. Finally, the waves that can propagate up to the satellite altitude are quasi aligned to the magnetic field direction at the altitude of the $X = 1$ plasma cutoff. Once this plasma cutoff has been crossed, all θ values are possible.

[34] At the present stage, some estimations on how the energy produced by wave interferences in the Earth ionosphere waveguide may be transmitted to the satellite altitude are given:

[35] 1. At the altitude of the $X = 1$ crossing, the propagation of the waves is more efficient for a small wave-normal vector, leading to an asymmetry of this particular V-shaped event at the DEMETER satellite altitude.

[36] 2. From that altitude to the satellite altitude, considering that the V-shaped emissions studied here have normalized frequency values $\Lambda = f/f_{ce}$ always smaller than 0.03 and considering the local parameter $f_p^2/(f\,f_{ce})$ is always higher than 1, it has been shown that the quasi-longitudinal approximation is valid up to the satellite altitude [*Helliwell*, 1965]. In this approximation, geometrical considerations of the wave-normal surfaces show that, along the raypath, the Poynting vector makes a maximum angle of 20° with the Earth magnetic direction, as represented in Figure 4c [see *Helliwell*, 1965, for more details], and so that the V-shaped events are broadly guided by the magnetic field up to the satellite altitude.

6. V-Shaped Observation on the 30 May 2008 Event: Asymmetric Observation in the Northern Hemisphere

[37] In this section, we illustrate with a case study the influence of the magnetic field inclination on the spectral form of the V-shaped emissions. Figure 5a shows the VLF spectrogram of the electric field recorded on 30 May 2008 between 20:52:00 UT and 20:57:30 UT. Many 0+ whistlers occur during this time interval. Their number and their intensity reach their maximum values around 20:54:44 UT. The observed V-shaped form is left asymmetric. The arms of the V pattern appear from 20:52:00 UT to 20:54:44 UT. Information about location, intensity, and polarity of all lightning occurring between 20:52:00 UT and 20:57:00 UT in the region below the satellite are provided by the METEORAGE network, which is a part of the Euclid lightning location network [*Diendorfer*, 2002]. The corresponding lightning locations are indicated by black crosses in the map of Figure 5b. The lightning activity is well confined within two major regions labeled E1 and E2. E1 is located at 48°N, 7°E whereas E2 is located at 52°N, 8°E.

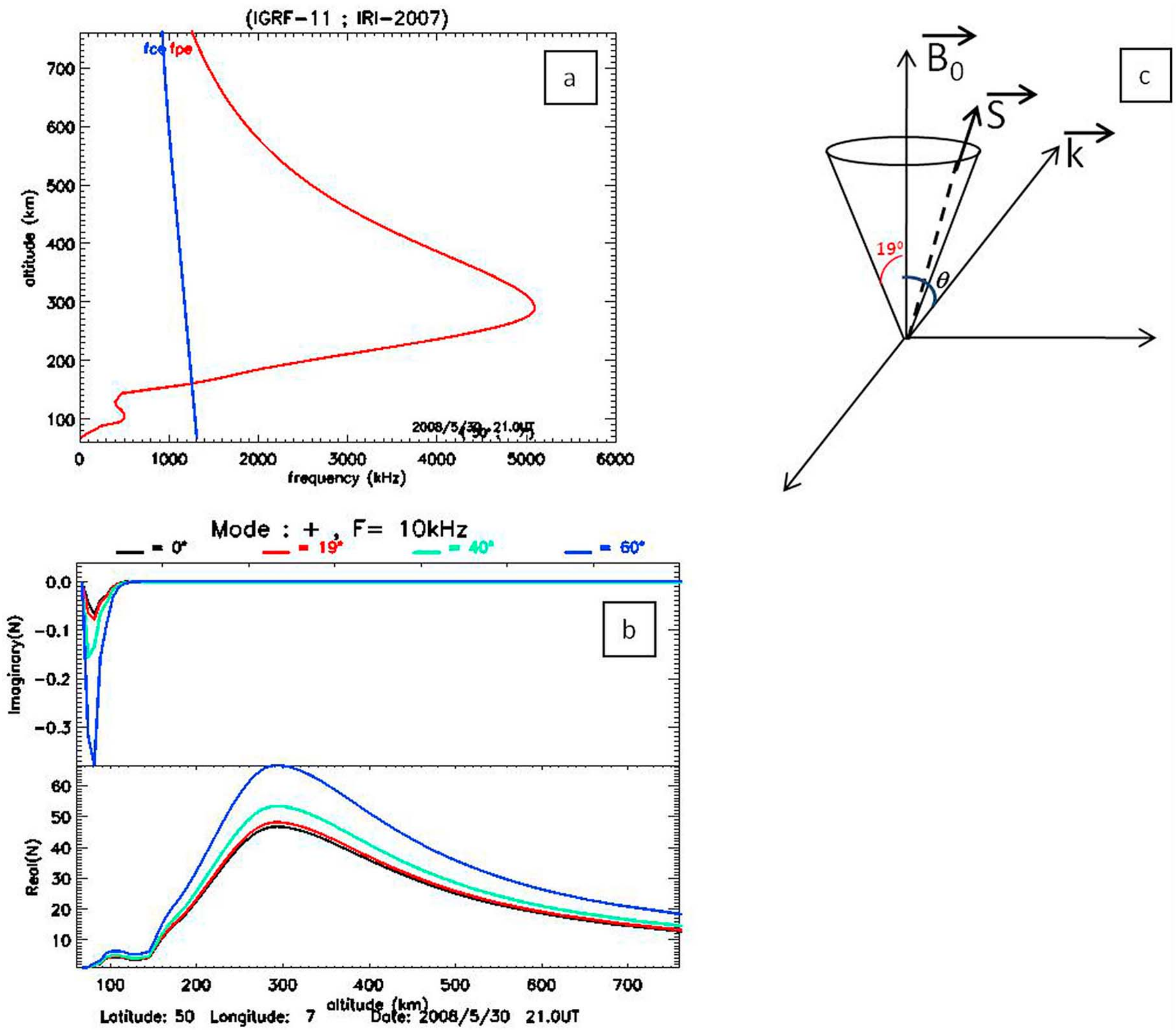

Figure 4. (a) The electron plasma frequency profile (red line) given by the IRI 2007 model for 30 May 2008 at 21 UT (longitude 7° and latitude 50°). The blue line is the electron gyrofrequency given by the IGRF-11 model. (b) Variation of the real and imaginary parts of the refraction index n with altitude h for f = 10 kHz. The electron plasma frequency is given by Figure 4a; the electron collision frequency profile is given by $\nu = 5 \times 10^6 \exp(-0.15(h - 70))$Hz. Calculations are made for θ = 0°,19°, 40°, and 60°, according to the color code. (c) Representative sketch of the direction of the Poynting vector S and the k vector with respect to the magnetic field B for the whistler mode. The θ angle represents the angle between the k vector and the magnetic field. Whatever θ is, the Poynting vector stays within the 19° cone axed along the magnetic field.

The red and black lines indicate different projections of the satellite position. The red line represents the magnetic footprint of the orbit, calculated at 100 km. The black line represents the vertical projection of the orbit onto the ground. The DEMETER satellite moves in a south to north path, as indicated by the black arrow on Figure 5b. The inclination angle of the local magnetic field at 20:54:44 UT is about 67°.

[38] By examining in parallel Figure 5a and 5b it is clear that the intensity of the 0+ whistlers reaches a maximum value when the satellite moves above the E2 area. In addition, one can notice that the E2 position is connected to the magnetic footprint of the satellite around 20:54:30 UT, whereas the E1 position is not connected. We can thus safely conclude that the lighting discharges responsible for the observations are those associated with the E2 location where the propagation to the satellite altitude necessarily follows the magnetic field line.

[39] For this case study, the asymmetry of the observed V-shaped pattern is explained by the sketch in Figure 5c. In the first step, a symmetrical V pattern that is due to interference modes of the Earth-ionosphere waveguide is produced by lightning strokes just above the E2 region where the inclination of the local magnetic field is about 67°; in that region, the inclination is such that the left-hand side of the interference pattern is observed on board the DEMETER satellite when it is approaching the lightning area. After 20:54:30 UT, the satellite moves away from the E2 area and

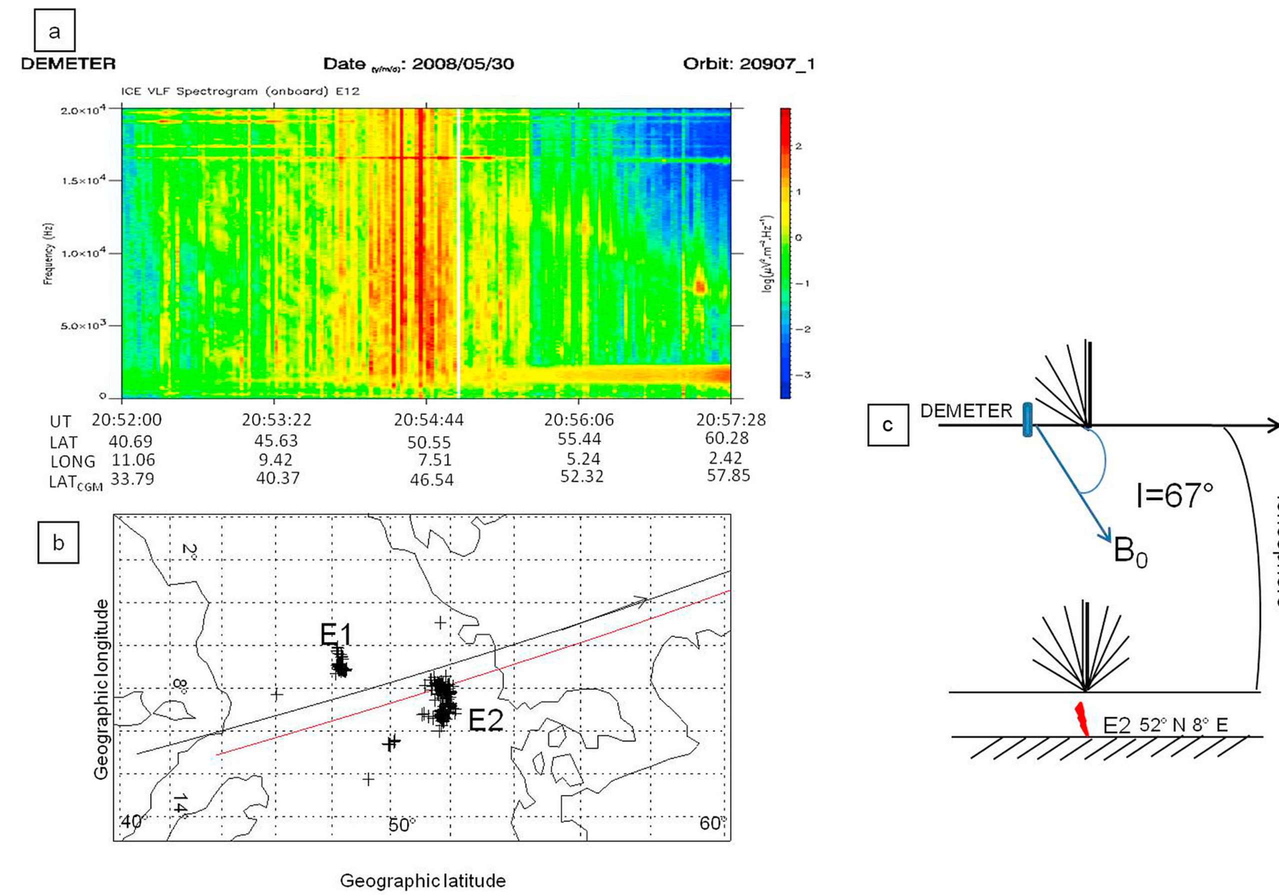

Figure 5. (a) Spectrogram of an electric component in the VLF range up to 20 kHz on 30 May 2008 between 20:52 and 20:58 UT. The parameters below the spectrograms indicate universal time (UT), local time (LT), geographic latitude and longitude, and the corrected geomagnetic latitude, denoted as lat_{CGM} and calculated using an IGRF model for the magnetic field. The intensity of the electric field is given by the color scale on the right. (b) Ground track of the DEMETER orbit is shown in black; the satellite moves following the direction of the vector on the track. The time interval corresponds to the time interval of Figure 5a; the red line shows the magnetic footprint. Two lightning areas denoted as E1 and E2 and detected during the time of observation by the METEORAGE network are represented with black crosses. (c) Summary plot of the event observed 30 on May 2008. Position of the lightning source labeled E2 is represented on geographical coordinates; inclination of the local magnetic field at the center of the observation is represented by the blue vector. The V pattern is represented at the top of the Earth-ionosphere waveguide and at the satellite altitude; see section 6 for more details.

the right-hand side of the V pattern is not observed on board the satellite. The local magnetic field configuration acts like a filter, and thus the right-hand side of the V-pattern is not detected at the satellite altitude. This is in agreement with the conclusions of guided propagation along magnetic field lines for altitudes higher than 100 km.

7. Summary and Conclusion

[40] In this paper we have focused on V-shaped emissions previously recorded on board the DEMETER satellite [*Parrot et al.*, 2008b] and related to high active thunderstorm areas and, more precisely, on asymmetric observations that, to our knowledge, are reported for the first time. Statistical study, modeling, and a detailed study of a characteristic event were conducted in order to explain the observed asymmetry.

[41] From the statistical study performed over 5 years, we make the following observations:

[42] 1. V-shaped events are clearly correlated with regions with high occurrence rates of thunderstorm lightning activity. Accordingly, they are mainly observed above continents and during summertimes where and when most of the thunderstorms occur.

[43] 2. Only a very few V-shaped events are observed within ±10° of geomagnetic latitudes despite the high lightning flash occurrence rates associated with the equatorial region. This anomaly is explained by the corresponding very small inclination of the local magnetic field, which leads to a penetration condition of VLF waves through the ionosphere that is very difficult to achieve.

[44] 3. Most of the asymmetric events are observed above regions of high geomagnetic latitudes. More precisely,

asymmetric events seem to be predominantly associated with regions of high local magnetic field inclinations.

[45] We have made the assumption that the orientation of the magnetic field can play a role in the observed spectral structures of the V-shaped emissions, where the 0+ whistler mode observed is broadly guided along the magnetic field line before reaching the altitude of the satellite.

[46] To test this assumption, a full wave propagation model has been used where the inclination of the magnetic field has been taken into account. The reconstructed spectrogram at 120 km of the simulated electromagnetic field exhibits the expected asymmetry. Higher intensity levels for high-frequency ranges (f > 10 kHz) are noticed. The asymmetry can be explained by the fact that the whistler waves penetrate through the ionosphere and propagate along magnetic field lines. However, numerical limitations, because of the size of the grid, did not allow us to perform a full wave simulation at higher altitudes.

[47] To complete this study, propagation conditions have been conducted using the cold plasma dispersive properties and plasma parameters (plasma frequency, electron gyrofrequency, collision frequency) provided by models at a given location. It has been shown that a kind of "k filtering" occurs: (i) the propagation of the waves up to the satellite altitude is more efficient for waves having wave-normal directions parallel or quasi parallel to the Earth magnetic field direction at the altitude of the $X = 1$ plasma cutoff, (ii) the k filtering process may explain the asymmetry of V-shaped events observed on board DEMETER when the satellite is over regions with high inclinations of the local magnetic field, and (iii) the wave energy propagates from the plasma cutoff to the satellite altitude with Poynting vectors making angles smaller than 20° with the Earth magnetic field direction.

[48] Finally, a particular event has been studied for which information about the localization of the lightning sources and local configurations of magnetic fields is available. This case study is consistent with the mapping of the waves along magnetic field lines.

[49] To conclude, it is important to note that the propagation process described in this paper does not explain the spectral signature of all the V-shaped events. For instance, as listed in Table 1, there are 48 symmetric V-shaped events belonging to the left asymmetric region in the Northern Hemisphere. In this paper we showed that, for DEMETER orbits passing away from a given thunderstorm but magnetically linked to the corresponding active lightning location, one may expect to observe an asymmetrical V-shaped event on board the DEMETER satellite depending on the local magnetic field inclination. However, it is known that very powerful thunderstorms with very intense lightning activity can heavily disturb the ionosphere just above them [*Inan et al.*, 2007]. In such a case, direct upward VLF propagation may happen, whatever the local magnetic field inclination. This could possibly explain the unexpected symmetric V-shaped events observed on board the DEMETER satellite for orbits passing just above the thunderstorm area. To solve this issue, a more detailed study of the unexpected symmetric V-shaped events is necessary and will be the subject of a future work. To achieve this goal, we will reinvestigate the DEMETER data from the beginning of the mission in order to build a complete V-shaped event database. Additionally, we also plan to study the effect of the geomagnetic activity on the signature of the observed V-shaped events.

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